

Abundance Anomalies in the X-ray Spectra of the Planetary Nebulae NGC 7027 and BD +30°3639

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ABSTRACT

We revisit *Chandra* observations of the planetary nebulae NGC 7027 and BD +30°3639 in order to address the question of abundance anomalies in the X-ray emitting gas. Enhanced abundances relative to solar of magnesium (Mg) for NGC 7027 and neon (Ne) for BD +30° 3639 are required to fit their X-ray spectra, whereas observations at optical and infrared wavelengths show depleted Mg and Ne in these systems. We attribute the enhancement of Mg in NGC 7027 in the X-ray, relative to the optical, to the depletion of Mg onto dust grains within the optical nebula. For BD +30° 3639, we speculate that the highly enhanced Ne comes from a WD companion, which accreted a fraction of the wind blown by the asymptotic giant branch progenitor, and went through a nova-like outburst which enriched the X-ray emitting gas with Ne.

Subject headings: planetary nebulae: general—planetary nebulae: individual (NGC 7027, BD +30°3639)—stars: winds, outflows—X-rays: ISM

1. Introduction

The optically emitting gas of planetary nebulae (PNs) is illuminated and ionized by the radiation from the central hot star, which is evolving to become a white dwarf (WD). The

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shaping of the optical nebula, formed from the envelope of the progenitor asymptotic giant branch (AGB) star, is a more complicated process, with many open questions (Kastner, Soker, & Rappaport 2000). Of particular interest is whether a binary companion is required to form non-spherical nebulae, or whether single AGB stars can blow axisymmetrical winds and form axisymmetrical PNs. According to Soker & Rappaport (2000) one of the processes by which a companion can shape a PN is by accreting from the wind of the AGB progenitor; if an accretion disk is formed around the compact companion, then a jet-like bipolar outflow (or collimated fast wind, CFW) can result. When the jet material is shocked, it heats up and may emit in the X-ray band. Another ingredient in the shaping process is the fast wind from the central star, blown during the post-AGB and PN stages (Kwok, Purton, & Fitzgerald 1978). The shocked fast wind is expected to emit in the X-ray band. In particular, an intermediate-velocity ($\sim 500 \text{ km s}^{-1}$) wind during the post-AGB phase may explain many of the observed properties of the X-ray emitting gas in PNs (Soker & Kastner 2003).

Processes behind the extended X-ray emission are tied to the shaping processes of PNs (Kastner *et al.* 2002), and although not all shaping processes will lead to X-ray emission, the X-ray properties of PNs may hint at the nature of their progenitor (Soker & Kastner 2003). With this goal in mind, we present a re-analysis of the spatially extended X-ray spectra of two PNs, BD +30°3639 (PN G064.7+05.5) and NGC 7027 (PN G084.9-03.4). Material relevant to these PNs is summarized in our earlier papers announcing the detection of extended X-ray emission from them (Kastner *et al.* 2000; Kastner, Vrtillek, & Soker 2001), and a study of the X-ray morphologies of these two PNs (Kastner *et al.* 2002). The observations are described in §2. In §3, we describe our spectral analysis, and in §4 we present the results, emphasizing the large differences in the abundances of some elements between the X-ray emitting gas and the optical nebula. In §4 we suggest explanations for these findings, focusing on magnesium (Mg) in NGC 7027, and neon (Ne) in BD +30°3639.

2. Observations

Chandra observed NGC 7027 for 19.0ksec and BD +30°3639 for 18.5ksec with the Advanced CCD Imaging Spectrometer (ACIS) (Garmire *et al.* 1988) as the focal plane instrument. For both observations the Science Instrument Module was translated and the telescope was pointed such that the telescope boresight was positioned near the center of the spectroscopy CCD array (ACIS -S); the objects were imaged on the central back-illuminated CCD (S3), which provides moderate spectral resolution of ~ 4.3 at 0.5 keV and ~ 9 at 1.0 keV. Analyses of these data have already appeared in Kastner *et al.* (2000,2001). Data from these observations were reprocessed by the Chandra X-ray Center (CXC) subsequent to the

publication of our earlier papers and the analyses presented here were performed on the reprocessed files. Each spectrum was extracted using the *Chandra* Interactive Analysis of Observations (CIAO) software within a region judged to contain all the X-ray flux from the nebula. We note that the current extraction (CIAOv2.2.1) reflects upgrades to the calibration system that were made after our previous papers on these systems were published. The extracted events are aspect-corrected, bias-subtracted, graded, energy-calibrated and limited to grade 02346 events (ASCA system). For both observations, the background count rate from a large, off-source annulus region (30- and 50-pixel radii) was negligible in comparison to the source count rate.

3. Spectral Analysis

The low photon statistics and limited energy range characteristic of these spectra make it difficult to derive abundances for these objects on the basis of X-ray spectra alone. Here we model the spectra using, as guidance, abundances derived from studies in the optical, ultraviolet, and infrared. We used the VMEKAL (Mewe, Lemen, & van den Oord 1986) code as incorporated into XSPEC v11.0 (Arnaud, Borkowski, & Harrington 1996) to generate model spectra that are appropriate for optically thin thermal plasma in ionization equilibrium. When abundance values for elements that are fit by VMEKAL are not available we set the abundance to Solar. In this we differ from our original papers (Kastner *et al.* 2000, 2001) where unspecified abundances were set to zero for elements heavier than Mg.

3.1. NGC 7027

The X-ray spectrum of NGC 7027 shows emission that peaks at approximately 0.9 keV and 1.3 keV and drops off at approximately 1.4 keV. No significant emission was detected below 0.5 keV and above 2.0 keV, hence we restrict our fits to the energy range 0.5-2.0 keV.

Nebular abundances reported by Bernard Salas *et al.* (2001) using ISO and optical observations produced a fair fit (Fig. 1), but do not adequately account for features between 0.6-0.7 keV and ~ 1.3 keV. We attribute the feature at 0.65 keV to a blend of O lines. We note that while the nebula has been reported to be somewhat depleted in O (Bernard Salas *et al.* 2001; Beintema *et al.* 1996; Keyes, Aller, & Feibelman 1990; Middlemass 1990), the stellar wind of NGC 7027 is expected to show a greatly enhanced O abundance (Hasegawa, Volk, & Kwok 2000). This high O abundance could explain the feature at 0.6 keV. However, we emphasize that, while Kastner *et al.* (2001, 2002) ascribe the X-ray emission to the action of a fast

wind, no such fast wind has yet been detected for this nebula. The feature at ~ 1.3 keV requires enhanced Mg abundance; we were unable to find alternative explanations for this feature. We thus fit our X-ray spectrum starting with nebular abundances as determined by Bernard Salas *et al.* (2001) but allowing O and Mg to be free. The resulting fit (Fig. 2 and Tables 1,2) requires O enhanced to 9 times solar and Mg enhanced to 3 times solar.

In all cases we allowed the intervening column density N_H to be a free parameter. Best-fit values of N_H (Table 2) are consistent with our previous results and with the typical value of A_V toward NGC 7027 (Kastner *et al.* 2001,2002); however, the temperature is a factor of ~ 2.8 larger, if the abundances of elements above Mg in NGC 7027 are Solar as assumed here. A higher temperature implies that the fast wind material that was shocked and formed the presently X-ray emitting gas was blown at a somewhat higher speed, and/or the adiabatic cooling, studied by Soker & Kastner (2003), was less efficient. ”

3.2. BD +30°3639

Like NGC 7027, past analysis of BD +30°3639 suggests that this PN’s X-ray emission arises primarily from wind and/or nebular material (Kastner *et al.* 2000). Here, we perform several tests to determine whether the observed X-ray spectrum is consistent with reported nebular and/or stellar wind abundances. The extracted spectrum shows distinct peaks near 0.5 keV and 0.95 keV. No significant emission was detected below 0.3 keV and above 1.5 keV. We restrict our fits to the energy range 0.3-1.5 keV.

We first assume nebular abundances reported from optical and ultraviolet observations by Pwa, Pottasch, & Mo (1986), Aller & Hyung (1995), and Grevesse & Sauval (1998). The best-fit parameters are listed in Table 2 and the model is shown in Figure 3. We then use abundances reported for the stellar wind by Arnaud *et al.* (1996). The stellar wind abundances provide a significantly better fit than the nebular abundances but strong features near 0.95 and 0.6 keV remain (Figure 4). We then attempted to fit the X-ray spectrum starting with the stellar wind abundances but allowing O and Ne to be free parameters. This resulted in an acceptable fit ($\chi^2 = 1.5$) with O enhanced to 3.6 times solar and Ne enhanced to 21 times solar. Although this Ne enhancement is not predicted by studies at longer wavelengths, it is consistent with earlier X-ray studies (Arnaud et al (1996); Kastner et al. (2000)) suggesting that the feature at 0.9 keV can only be fit with an enhanced Ne abundance. The model is shown overlaying the data in Figure 5, and the best-fit parameters are listed in Tables 1, 2. Our best-fit value for T is 0.7 times higher and for N_H two times higher than that obtained by Kastner et al. (2001), whose result for N_H is consistent with the measured optical obscuration of the nebula (A_V) given a conversion between N_H and

A_V appropriate for the interstellar medium. Our result for N_H would therefore suggest that the gas to dust ratio in this nebula is elevated over that of the interstellar medium, along lines of sight toward the X-ray-emitting gas.

4. Discussion and Conclusions

NGC 7027 and BD +30°3639 show strong emission features that require enhanced Mg abundance relative to solar (to fit lines at ~ 1.3 keV) for NGC 7027, and enhanced Ne abundance relative to solar (to fit lines at ~ 0.9 keV) for BD +30°3639 (Kastner *et al.* 2000; Kastner *et al.* 2001). Both of these results are surprising since abundance values for the nebular and stellar wind material obtained at other wavelengths indicate depleted Mg and Ne (Beintama *et al.* 1996; Keyes & Aller 2001; Middlemass 1990).

4.1. Neon in BD +30°3639

Kastner *et al.* (2000) proposed that the high abundance of Ne found in BD +30°3639 results from the central star which itself is a carbon-rich Wolf-Rayet ([WC]) object (Grosdidier *et al.* 2000). Here we suggest that the source of the large abundance of Ne in BD +30°3639 is a nova eruption on an oxygen-neon-magnesium (ONeMg) WD companion. Novae in cataclysmic variables, which are thought to occur on the surface of ONeMg WDs, are known to eject material with Ne abundance up to ~ 300 times the solar abundance, and the total ejected mass is $\gtrsim 10^{-5} - 10^{-4} M_\odot$ (Starrfield *et al.* 1998). The estimated mass in the X-ray emitting gas in BD +30°3639 is $\sim 2 \times 10^{-5} M_\odot$ (Kastner *et al.* 2000). Therefore, a nova eruption can easily account for the ~ 21 times solar Ne abundance. The Mg abundance in such nova eruptions is typically a factor of $\sim 5 - 50$ times lower than the Ne abundance (Starrfield *et al.* 1998). Therefore, it is not surprising we do not detect the Mg line in the spectrum of BD +30°3639.

The shaping of some bipolar PNs by nova eruption on a WD companion has been proposed by Soker (2002), who reviews many routes for the formation of bipolar PNs, several involving novae eruptions. The accretion rate onto the WD cannot be too high in that case, so the orbital separation cannot be too small. We do note that an accretion disk may mix Ne in the ejected jets even when there is steady nuclear burning. Observations supporting this proposed scenario come from symbiotic systems. Some symbiotic systems are known to experience nova outbursts (such systems are referred to as "symbiotic novae"; e.g., RX Puppis, Mikolajewska *et al.* 1999), and some bipolar symbiotic nebulae appear to have gone

through an eruptive mass loss event, possibly due to a nova eruption, as in the cases of V1016 Cyg (Corradi et al. 1999) and He 2-104 (Corradi et al. 2001). For the symbiotic nova RX Puppis, Mikolajewska et al. (1999) argue for an orbital separation of $\gtrsim 50$ AU. Although the bright ionized region of BD +30°3639 has a general elliptical shape, high resolution radio molecular-line imaging has revealed the presence of two, oppositely-directed “bullets” of fast-moving, dense gas, suggestive of the action of collimated outflows or jets (Bachiller et al. 2000). To conclude, we propose that the central star of BD +30°3639 has a massive, $M_{\text{WD}} \sim 1M_{\odot}$ ONeMg WD companion, at an orbital separation of $\sim 5 - 50$ AU.

4.2. Magnesium in NGC 7027

In principle, peculiar abundance in the X-ray emitting gas of NGC 7027 could also result from material ejected from a WD companion; indeed, Kastner et al. (2001) attributed the emission peak near 0.9 keV to Ne lines (whereas here they are modeled as a complex of lines of highly ionized Fe). However, we suggest a simpler explanation. The nebular abundances derived from previous studies of NGC 7027 are for the gas in the optical nebulae, and do not include metals locked in dust particles. NGC 7027 is known to have a significant amount of dust in the nebular shell (Sanchez Contreras *et al.* 1998) hence it is expected that many metals will be depleted in the gas phase. However, in the X-ray emitting gas we don’t see this depletion, which implies that the dust in this medium was either destroyed or was never formed.

Assuming that the Mg abundance in the X-ray emitting gas is that of the wind lost by the progenitor, then the depletion in this nebula is by a factor of $3.0/0.58 \simeq 5$ (Table 1). Mg depletion in PNs is well established. For example, in the galactic PN NGC 3918, Harrington, Monk, & Clegg (1988) find depletion by a factor of 3. Dopita et al. (1997) find Mg depletion by a factor of ~ 20 in PNs in the Magellanic Clouds and note that Mg is not expected to be formed or destroyed during the evolution of these PNs (since an ONeMg WD is not formed), and that the magnesium resides in dust grains which are not destroyed by the UV radiation of the central star. The depletion fraction we find, then, implies that the star was born with a Mg abundance of ~ 3 times the solar value. This is feasible, since the distance of NGC 7027 from the galactic center is similar to that of the sun, and it is close to the galactic plane. Mg abundance of ~ 3 times solar are found in the solar neighborhood and closer to the galactic center (e.g., Smartt *et al.* 2001).

In addition, a high Mg abundance due to destruction of dust is unlikely because the destruction time of the dust in this PN is likely to be longer than the time elapsed since the star left the AGB, which we deduce in the following way. The destruction time of dust

particles in the temperature range $5 \times 10^5 K \lesssim T_x \lesssim 5 \times 10^7 K$ depends weakly on the temperature (Draine & Salpeter 1979; Smith et al. 1996). However, the destruction time depends on the grain size. For the PN NGC 3918, for example, Harrington *et al.* (1988) find that $\sim 50\%$ of the dust mass is in dust particles of size $a \gtrsim 0.1 \mu\text{m}$. In NGC 7027, the dust grains may be much larger, with sizes of $a \gtrsim 0.1 \mu\text{m}$, and up to $a \sim 5 - 20 \mu\text{m}$ (Sanchez Contreras *et al.* 1998). Scaling from Draine & Salpeter (1979) for values appropriate here, in particular grain sizes of $0.1 \mu\text{m}$ (Jura 1996), we find the destruction time of dust in NGC 7027 is longer than

$$\tau_d \sim 1500 \left(\frac{n_e}{150 \text{cm}^{-3}} \right)^{-1} \left(\frac{a}{0.1 \mu\text{m}} \right) \text{ yr}$$

For an ISM distribution of grain sizes the destruction time at a pressure of $P \simeq 10^9 \text{ cm}^{-3} \text{ K}$, as in the X-ray emitting gas of NGC 7027, is $\sim 2500 \text{ yr}$, according to the calculation of Smith et al. (1996). The nebular dust cannot be destroyed in the shock, since the shock moving through the optical-nebular gas is relatively slow. The dynamical age of NGC 7027 is $< 1000 \text{ yr}$ (Masson 1989; Latter et al. 2000). We conclude that the dust can't be destroyed, even if the nebular gas is heated to $\sim 10^7 \text{ K}$. Because the dust cannot be destroyed for this PN, we speculate that the X-ray emitting gas results from wind segments which never formed dust. These segments could result either from a post-AGB wind or a CFW blown by an accreting companion (for discussion of these possibilities see Soker 2002).

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5. References

- Aller, L. H. & Hyung, S. 1995, MNRAS, 276, 1101
- Arnaud, K., Borkowski, K. J., & Harrington, J. P. 1996, ApJ, 462, L75
- Bachiller, R.; Forveille, T.; Huggins, P. J.; Cox, P.; Maillard, J. P. 2000, A&A 353, L5
- Bernard Salas, J., Pottasch, S. R., Beintema, D. A., & Wesselius, P. R. 2001, A&A, 367, 949
- Beintema, D. A. et al. 1996, A&A, 315, L253

- Corradi, R. L. M., Ferrer, O. E., Schwarz, H. E., Brandi, E., & Garcia, L. 1999, *A&A*, 348, 978
- Corradi, R. L. M., Livio, M., Balick, B., Munari, U., & Schwarz, H. E. 2001, *ApJ*, 553, 211
- Dopita, M. A. et al. 1997, *ApJ*, 474, 188
- Draine, B. T. & Salpeter, E. E. 1979, *ApJ*, 231, 77
- Garmire, G. P., Nousek, J., Burrows, D., Ricker, G., Bautz, M., Doty, J., Collins, S., & Janesick, J. 1988, *Proc. SPIE*, 982, 123
- Grevasse, N. & Sauval, A. J. 1998, *Space Science Reviews*, 85, 161
- Grosdidier, Y., Acker, A.i, & Moffat, A. F. J. 2000, *A&A*, 364, 597
- Harrington, J. P., Monk, D. J., & Clegg, R. E. S. 1988, *MNRAS*, 231, 577
- Hasegawa, T., Volk, K., & Kwok, S. 2000, *ApJ*, 532, 994
- Jura, M. 1996, *ApJ*, 472, 806
- Kastner, J., Li, J., Vrtilik, S., Gatley, I., Merrill, K., & Soker, S. 2002, *ApJ*, in press
- Kastner, J., Soker, N., & Rappaport, S. 2000, *ASP Conference Series*, Vol. 199. Eds. J. H. Kastner, N. Soker, and S. Rappaport
- Kastner, J. H., Soker, N., Vrtilik, S. D., & Dgani, R. 2000, *ApJ*, 545, L57
- Kastner, J. H., Vrtilik, S. D., & Soker, N. 2001, *ApJ*, 550, L189
- Keyes, C. D., Aller, L. H., & Feibelman, W. A. 1990, *PASP*, 102, 59
- Kwok, S., Purton, C. R., & Fitzgerald, P. M. 1978, *ApJ*, 219, L125
- Latter, W. B., Dayal, A., Bieging, J. H., Meakin, C., Hora, J. L., Kelly, D. M., & Tielens, A. G. G. M. 2000, *ApJ*, 539, 783
- Masson, C. R. 1989, *ApJ*, 336, 294
- Mewe, R., Lemen, J.R., & van den Oord, G.H.J. 1986, *A&AS*, 65, 511
- Middlemass, D. 1990, *MNRAS*, 244, 294
- Mikolajewska, J., Brandi, E., Hack, W., Whitelock, P., A., Barba, R., Garcia, L., & Marang, F. 1999, *MNRAS*, 305, 190
- Pwa, T. H., Pottasch, S. R., & Mo, J. E. 1986, *A&A*, 164, 184

- Sanchez Contreras, C., Alcolea, J., Bujarrabal, V., & Neri, R. 1998, *A&A*, 337, 233
- Smartt, S. J., Venn, K. A., Dufton, P. L., Lennon, D. J., Rolleston, W. R. J., & Keenan, F. P. 2001, *A&A*, 367, 86
- Smith, R. K., Krzewina, L. G., Cox, D. P., Edgar, R. J., & Miller, W. W. I. 1996, *ApJ*, 473, 864
- Soker, N. 2002, *MNRAS*, 330, 481
- Soker, N. & Kastner, J. H. 2003, *ApJ*, in press, (astro-ph/0209139)
- Soker, N. & Rappaport, S. 2000, *ApJ*, 538, 241
- Starrfield, S., Truran, J. W., Wiescher, M. C., & Sparks, W. M. 1998, *MNRAS*, 296, 502

Table 1: Abundances used in fits

Element	NGC 7027		BD+30°3639		
	BSPBW ^a	This paper ^b	AH ^c	ABH ^d	This paper ^e
He	1.08	1.08	1	1	1
C	1.69	1.69	1.1	354	354
N	1.71	1.71	1.0	9.1	9.1
O	0.55	9.2±2	0.44	1.26	4.2±0.3
Ne	0.83	0.83	0.01	10.5	19.3±1.4
Na	0.58	0.58	1	1	1.
Mg	0.58	3.0±1	1	1	1.
Si	0.17	0.17	1	1	1
S	0.51	0.51	0.33	1	1
Ar	0.63	0.63	0.05	1	1
Fe	1	1	1	0	0
χ^2_ν	2.0	0.9	9.3	2.1	1.2

^aBernard Salas *et al.* (2001) nebular abundances.

^bAs in BSPBW but with abundances for O and Mg allowed to be free.

^cAller & Hyung (1995) nebular abundances.

^dArnaud *et al.* (1996) stellar wind abundances.

^eAs in ABH but with O and Ne allowed to be free.

Table 1. Model Parameters for Spectral Fits

Object/Model	N_H (x $10^{20}cm^{-2}$)	T (x 10^6 K)	Flux (ergs cm^{-2} s $^{-1}$)	χ^2_ν
NGC 7027 (0.5-2.0 keV)				
Nebular	70 \pm 3	7.9 \pm 0.6	3.0e-14	2.0
Modified Nebular	41 \pm 2	8.4 \pm 0.6	3.6e-14	0.9
BD +30$^\circ$ 3639 (0.3-1.5 keV)				
Nebular	74 \pm 2	1.2 \pm 0.02	4.8e-13	9.3
Stellar Wind	24 \pm 1	2.1 \pm 0.02	6.1e-13	2.1
Modified Stellar Wind	25 \pm 1	2.1 \pm 0.02	6.1e-13	1.2

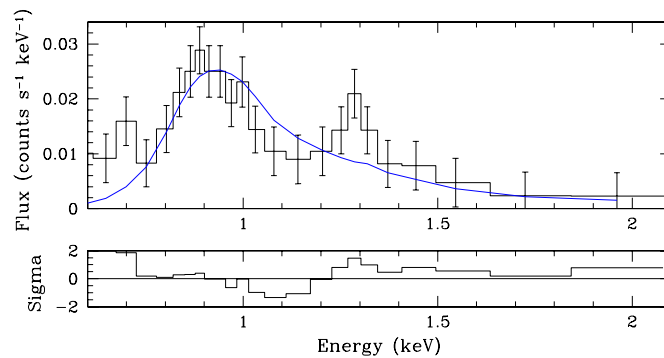


Fig. 1.— X-ray spectrum of NGC 7027 with Bernard Salas *et al.* (2001) nebular model overlaid.

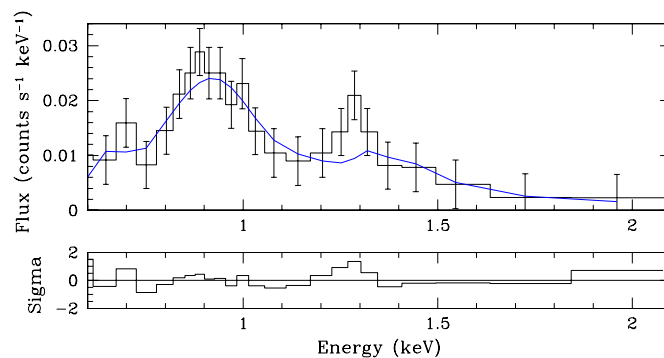


Fig. 2.— X-ray spectrum of NGC 7027 with modified nebular model overlaid.

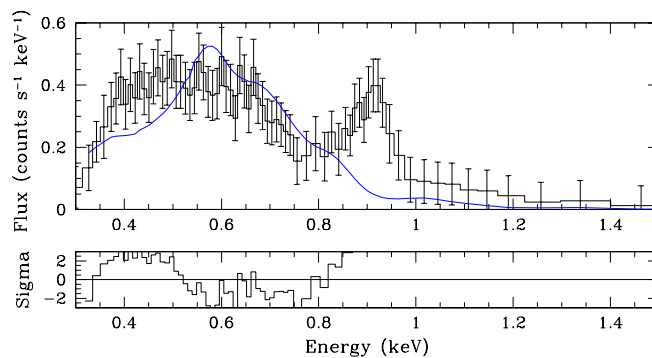


Fig. 3.— X-ray spectrum of BD +30° 3639 with Aller and Hyung (1995) nebular model overlaid.

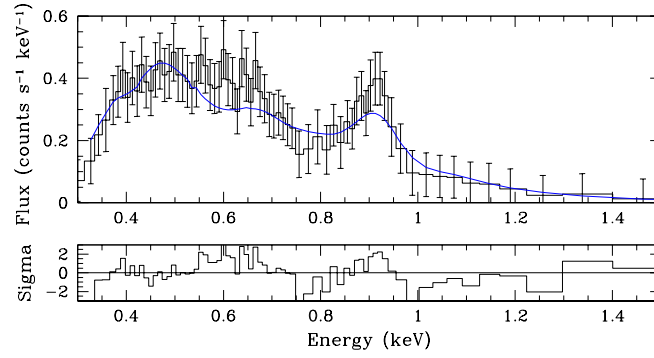


Fig. 4.— X-ray spectrum of BD +30° 3639 with Arnaud *et al.* (1996) stellar wind model overlaid.

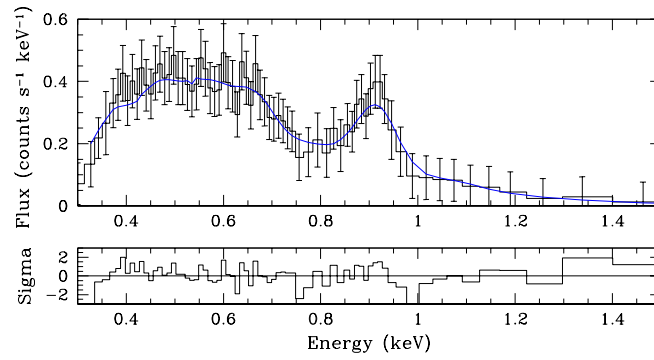


Fig. 5.— X-ray spectrum of BD +30° 3639 with modified stellar wind model overlaid.